JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
VOL. 37, NO. 5 AMERICAN WATER RESOURCES ASSOCIATION OCTOBER 2001

BANKFULL DISCHARGE RECURRENCE INTERVALS AND REGIONAL HYDRAULIC GEOMETRY RELATIONSHIPS: PATTERNS IN THE PACIFIC NORTHWEST, USA[1]

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ABSTRACT: The model bankfull discharge recurrence interval (annual series) (T_a) in streams has been approximated at a 1.5-year flow event. This study tests the linkage between regional factors (climate, physiography, and ecoregion) and the frequency of bankfull discharge events in the Pacific Northwest (PNW). Patterns of Ta were found to be significant when stratified by EPA Ecoregion. The mean value for T_a in the PNW is 1.4 years; however, when the data is stratified by ecoregion, the humid areas of western Oregon and Washington have a mean value of 1.2 years, while the dryer areas of Idaho and eastern Oregon and Washington have a mean value of 1.4 to 1.5 years. Among the four factors evaluated, vegetation association and average annual precipitation are the primary factors related to channel form and T_a. Based on the results of the T_a analyses, regional hydraulic geometry relationships of streams were developed for the PNW, which relate variables, such as bankfull cross-sectional area, width, depth, and velocity, to bankfull discharge and drainage area. The verification of T_a values, combined with the development of regional hydraulic geometry relationships, provides geographically relevant information that will result in more accurate estimates of hydraulic geometry variables in the PNW.
(KEY TERMS: hydraulic geometry; bankfull discharge recurrence interval; surface water hydrology; hydraulics, channel-forming flow; regional curves; ecoregion.)

INTRODUCTION

"Bankfull stage" is defined as the stream level that "corresponds to the discharge at which channel maintenance is most effective, that is, the discharge at which moving sediment, forming or reforming bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels" (Dunne and Leopold, 1978). The morphologic characteristics of a stream channel include several of the variables that can be derived from regional curves when the drainage area or bankfull discharge are known. It follows that when using regional curves, the stream in question should fall within a geographic region which has similar bankfull discharge recurrence intervals.

Research on bankfull discharge for North American streams has resulted in general agreement that the annual series bankfull discharge recurrence intervals (T_a) are approximately equal to a 1.5-year event, (Dury *et al.,* 1963; Leopold *et al.,* 1964; Hickin, 1968; Dunne and Leopold, 1978; Leopold, 1994). Williams (1978) however, found that while the mode value of bankfull discharge recurrence for 36 active floodplain stations he observed was approximately a 1.5-year event, the large variability in his data set (one to 32 years) caused this 1.5-year interval to be of little value for the stations evaluated. Nolan *et al.* (1987) suggested that there is a link between stream channel type and T_a and that this relationship may explain some of the variability found in the recurrence intervals. This paper tests such a linkage in the context of regional factors potentially related to stream channel morphology.

The development of regional curves and hydraulic geometry variables of stream channels represents a symbolic and functional change from the qualitative geomorphology practiced in the early part of the 20th century to the quantitative geomorphology more characteristic of the field during the past 50 years. A seminal work by Leopold and Maddock (1953) introduced quantitative geomorphology by the way of the hydraulic geometry of stream channels. This work encouraged further quantification of stream analyses

[1]Paper No. 00048 of the *Journal of the American Water Resources Association.* **Discussions are open until June 1, 2002.**
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and directed much of the research in fluvial geomorphology. The spatial variation of hydraulic geometry studies during the past several decades has been expansive (Leopold and Maddock, 1953; Richards, 1973; Knighton, 1974; Park, 1977; Williams, 1987; Hogan and Church, 1989; Merigliano, 1997), ranging from Hogan and Church's (1989) evaluation the hydraulic geometry of two small streams on the west coast of the Queen Charlotte Islands in British Columbia, Canada, to Park's (1977) world-wide perspective of the variability of hydraulic geometry exponents.

Even though there has been extensive research in hydraulic geometry, there is surprisingly little data concerning regional relationships. Leopold (1994) has been the foremost proponent of using regional curves and regression equations to estimate expected levels of bankfull discharge and cross-sectional area. Regional curves have been generated by Leopold (1994) and have proved to be applicable and useful in the field; however, these curves have no set geographic limits for application.

Data were collected on 76 streams in the Pacific Northwest (PNW) region (Oregon, Washington, and Idaho) during the summer of 1995 (Figure 1, Table 1). The stream survey data were compiled for analyses of T_a and hydraulic geometry; using bankfull discharge, cross-sectional area, width, depth, and drainage area as variables, regional regression equations were generated for various regions within the PNW (Table 1), allowing for the estimation of bankfull cross-sectional area, width, depth, velocity, and discharge for ungaged streams within the respective regions.

Information on bankfull stage has applied importance for the design of fish habitat structures, stream restoration designs, and other instream and riparian work. By providing approximations of the T_a, scientists and managers can more accurately estimate both physical and biological responses to stream corridor manipulations and estimate project costs. It is our position that stream management strategies, especially those designed to assist stream restoration work, should be geographically relevant and operate within an understanding of regional relationships between channel types and variability in T_a.

OBJECTIVES

The major objectives of this study are: (1) to test the validity of the 1.5-year bankfull discharge recurrence interval assumption, (2) to define broad-scale regional patterns based on recurrence intervals, and (3) to generate geographic/spatial relationships for stream discharge and channel hydraulics stratified by appropriate geographic regions.

STUDY AREA

The study area includes selected PNW watersheds in Oregon, Washington, and Idaho. U.S. Geological Survey (USGS) hydrologic units are the sampling units and the criteria for stream selection is all active stream gages within a selected hydrologic unit. All streams associated with an active gage are evaluated, so there is complete selection within the sample unit.

Climate

The climatic patterns of the Pacific Northwest were regionalized according to the Köppen-Geiger (1930) classification system which takes into account the amount and type of precipitation, temperature, seasonality, and vegetative associations. The Köppen system was chosen because of its widespread use and general academic acceptance and because of the ease of application to the Pacific Northwest (Trewartha and Horn, 1980). The Pacific Northwest can be classified into three broad Köppen climate regions: the mid-latitude steppe (BSk) summarizes the character of the interior dry climate area; the mesothermal climates, predominately subtropical dry-summer (Csb) and west coast (Cfb), are found in much of the region west of the Cascade Range; and the mountainous areas, including the Cascades and interior ranges to the east, are classified as microthermal, summer-dry continental, and humid continental climates (Ds, Df) (Figure 2) (Jackson, 1992).

The mid-latitude steppe region (BSk) is typified where potential evaporation exceeds precipitation. The factors of rainshadow, interior location, high elevation, semi-permanent high-pressure, and cold, dry, polar air influence in winter combine to produce aridity and large seasonal temperature ranges. Peak runoff in locally fed streams occurs in late spring as convective rainstorms melt foothill and mountain snowpacks. Except for the Columbia Basin and the Snake River Plain, much of the runoff results in intermittent stream flow and interior drainage.

A modest seasonal temperature range and heavy cool season precipitation characterize the mesothermal climates (C) of the PNW. The Csb climate, known as dry-summer subtropical, is found from west of the Cascade Range to the Pacific Ocean and includes the Rogue, Willamette, and Puget lowlands. The marine west coast climate (Cfb) has year-round precipitation

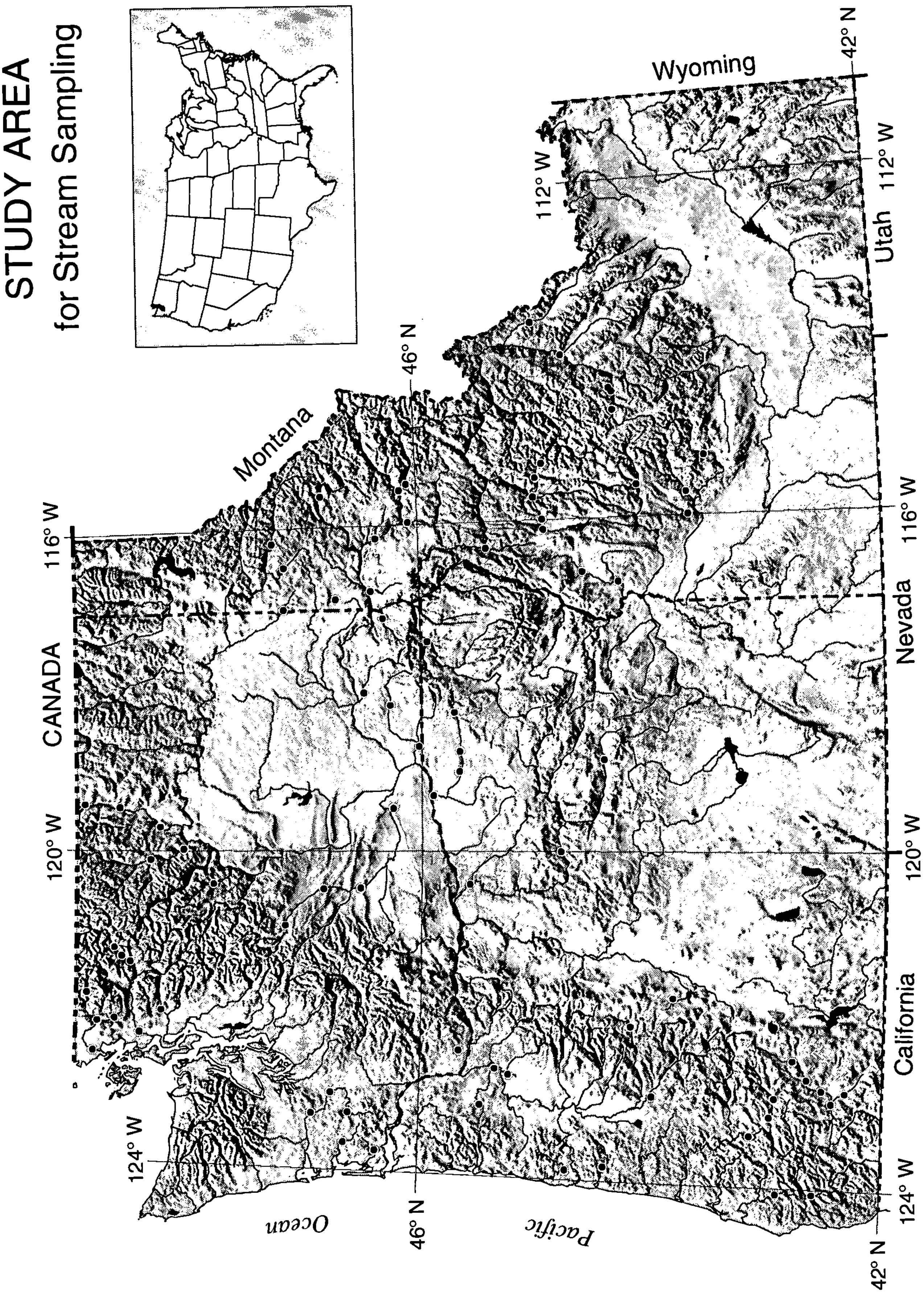

Figure 1. Study Area for Stream Sampling.

TABLE 1. Pacific Northwest Stream Data.

Gage Station	Station Name	State	Discharge (cfs)	Bankfull Width (ft)	Bankfull Depth (ft)	Cross-Section Area (ft^2)	Slope (percent)	Return Period (years)	Drainage Area (Mi^2)
12414500	St. Joe	ID	12300	260	6.2	1612	0.14	1.2	1030
12414900	St. Maries	ID	2041	95	3.4	323	0.32	1.32	275
12422950	Hangman	ID	320	40	2.7	108	0.15	1.0	125
13185000	Boise	ID	3342	180	4.4	792	0.70	1.07	830
13186000	S.F. Boise	ID	2406	125	3.8	475	0.43	1.16	635
13200000	Mores	ID	932	75	2.9	214	0.58	1.34	399
13235000	S.F. Payette	ID	4763	155	5.3	821	0.61	2.6	456
13239000	N.F. Payette	ID	2707	60	3.4	204	0.59	1.61	144
13240000	Lake Fork Payette	ID	394	95	3.9	370	1.60	1.01	48.9
13258500	Weiser	ID	1327	70	3.6	252	0.49	1.04	605
13266000	Weiser	ID	4016	220	3.4	748	0.25	1.09	1460
13296500	Salmon	ID	3600	120	6.8	816	0.83	1.36	802
13297330	Thompson	ID	137	28	1.1	31	1.82	2.2	29.1
13297355	Squaw	ID	154	36	1.4	49	1.48	1.3	79
13305000	Lemhi	ID	932	60	2.6	159	1.90	1.81	895
13310700	S.F. Salmon	ID	2878	115	5.4	621	0.39	1.71	330
13311000	E.F. of S.F. Salmon	ID	338	36	1.8	65	4.30	1.85	19.6
13313000	Johnson	ID	2680	100	4.2	420	1.18	1.72	213
13316500	Little Salmon	ID	3269	84	4.0	336	1.33	1.16	576
13336500	Selway	ID	18860	310	8.4	2604	0.40	1.24	1910
13337000	Lochsa	ID	18190	280	7.8	2184	0.30	1.86	1180
13338500	S.F. Clearwater	ID	5395	200	4.5	900	0.47	1.54	1150
13339500	Lolo	ID	1311	75	3.7	277	1.25	1.56	243
13340600	N.F. Clearwater	ID	12910	300	8.7	2610	0.44	1.16	1360
13346800	Paradise	ID	154	13	2.7	35	0.56	1.4	17.7
13333000	Grande Ronde	OR	11160	200	5.8	1160	0.33	1.39	3275
14021000	Umatilla	OR	2409	120	3.9	463	0.21	1.09	637
14026000	Umatilla	OR	3870	125	4.2	527	0.26	1.26	1280
14038530	John Day	OR	530	82	1.8	1.48	0.57	1.12	386
14046500	John Day	OR	11770	225	7.7	1732	0.32	1.84	5090
14048000	John Day	OR	6257	285	4.4	1254	0.73	1.13	7580
14050000	Deschutes	OR	280	60	1.6	93.6	0.31	2.44	132
14157500	C. F. Willamette	OR	3075	162	4.5	726	0.16	1.01	642
14202000	Pudding	OR	2008	105	8.6	903	0.08	1.0	479
14203500	Tualatin	OR	720	53	2.0	108	0.05	1.0	125
14207500	Tualatin	OR	2806	165	4.7	775	0.52	1.01	706
14305500	Siletz	OR	4769	160	6.3	1008	0.28	1.0	202
14306500	Alsea	OR	3522	140	5.4	756	0.22	1.0	334
14308000	S. Umpqua	OR	8545	90	7.1	639	0.33	1.09	449
14308600	S. Umpqua	OR	9234	147	4.5	661	0.36	1.06	641
14312000	S. Umpqua	OR	9923	340	9.0	3060	0.13	1.02	1670
14325000	S.F. Coquille	OR	2447	150	3.7	562	0.39	1.0	169
14328000	Rogue	OR	5314	160	4.1	664	1.07	2.95	312
14337600	Rogue	OR	9497	180	8.7	1566	0.48	2.2	938
14339000	Rogue	OR	14830	240	6.3	1507	0.25	1.52	1215
14357500	Bear	OR	1434	62	3.3	205	0.82	1.95	289
14359000	Rogue	OR	15250	260	11.5	2990	0.14	1.37	2053
14372300	Rogue	OR	28440	360	13.1	4716	0.10	1.18	3939

TABLE 1. Pacific Northwest Stream Data (continued).

Gage Station	Station Name	State	Discharge (cfs)	Bankfull Width (ft)	Bankfull Depth (ft)	Cross-Section Area (ft^2)	Slope (percent)	Return Period (years)	Drainage Area (Mi^2)
12010000	Naselle	WA	2248	95	4.6	437	0.47	1.0	54.8
12013500	Willapa	WA	1509	90	6.5	585	0.06	1.0	130
12027500	Chehalis	WA	12670	300	14.6	4380	0.10	1.01	895
12031000	Chehalis	WA	8443	280	16.6	4648	0.07	1.0	1294
12167000	N.F. Stillaguamish	WA	20630	260	8.9	2314	0.16	1.45	262
12178000	Skagit	WA	12770	210	8.7	1827	2.50	1.27	1175
12179000	Skagit	WA	15000	240	10.3	2472	0.40	1.32	1274
12181000	Skagit	WA	15040	350	6.5	2275	0.17	1.15	1381
12200500	Skagit	WA	39640	600	16.3	9780	0.02	1.06	3093
12205000	N.F. Nooksack	WA	4527	90	5.6	504	1.05	1.41	105
12209000	S.F. Nooksack	WA	7606	125	6.0	750	0.19	1.42	103
12210500	Nooksack	WA	11670	250	8.7	2175	0.13	1.01	584
12213100	Nooksack	WA	9797	220	12.1	2662	0.04	1.0	786
12445000	Okanogan	WA	7071	195	9.0	1755	0.08	1.04	7260
12447200	Okanogan	WA	12800	245	11.1	2719	0.10	1.35	8080
12449500	Methow	WA	11570	200	6.3	1260	0.30	2.01	1301
12449950	Methow	WA	8897	110	5.5	605	0.51	1.36	1772
12452800	Entiat	WA	1920	80	4.4	352	0.21	1.25	203
12479500	Yakima	WA	3520	270	4.4	1188	0.29	2.95	
12484500	Yakima	WA	10700	220	7.3	1606	0.18	3.11	1594
12500450	Yakima	WA	8037	230	7.2	1656	0.24	1.25	3479
12510500	Yakima	WA	7214	250	5.5	1375	0.08	1.16	5615
13334700	Asotin	WA	528	28	2.2	62	1.40	2.63	170
13344500	Tucannon	WA	929	45	2.4	108	0.51	1.45	431
14017000	Touchet	WA	940	65	2.0	130	0.43	1.15	361
14018500	Walla Walla	WA	1731	92	4.8	445	0.10	1.03	1657
14222500	E.F. Lewis	WA	3363	120	5.9	708	0.77	1.02	125

and is limited geographically to the Olympic Peninsula; however, much of the PNW coastal zone is humid, even in summer, due to heavy night and morning fog formation. Winter months are dominated by zonal jet stream flows with embedded frontal cyclonic storms that produce copious amounts of precipitation in the Coast Ranges of Oregon and Washington. Coastal rivers respond rapidly to these storm events, with highest stream flow levels occurring intermittently from December through March. Peak runoff events occur under wet antecedent conditions, with heavy rains falling on melting mountain snowpacks.

The microthermal climates (D) occur throughout the major mountain areas with cold, snowy winters and warm, short summers. The Dsb climate, a dry-summer continental classification, is somewhat unique, mapped by Köppen and Geiger (1930) as occurring only in the PNW and in the Pantid Mountains extending through northern Turkey and Iraq. Annual snowfall in the western Cascades is almost seven times larger than totals in the Blue Mountains of eastern Oregon and Washington and the Rocky Mountains further east in Idaho. Runoff is chiefly from snowmelt, peaking in the late spring and early summer.

Physiography

Major physiographic divisions of the Pacific Northwest (Fenneman, 1946) include the Intermontane Plateaus, the Pacific Mountain System, and a portion of the Rocky Mountain System (Figure 3). The Intermontane Plateau within the study area is represented by the Columbia Plateau, which encompasses approximately 100,000 square miles of Washington, Oregon, and Idaho. The boundaries are the Cascade Range to the west, the Rocky Mountain Province to the north

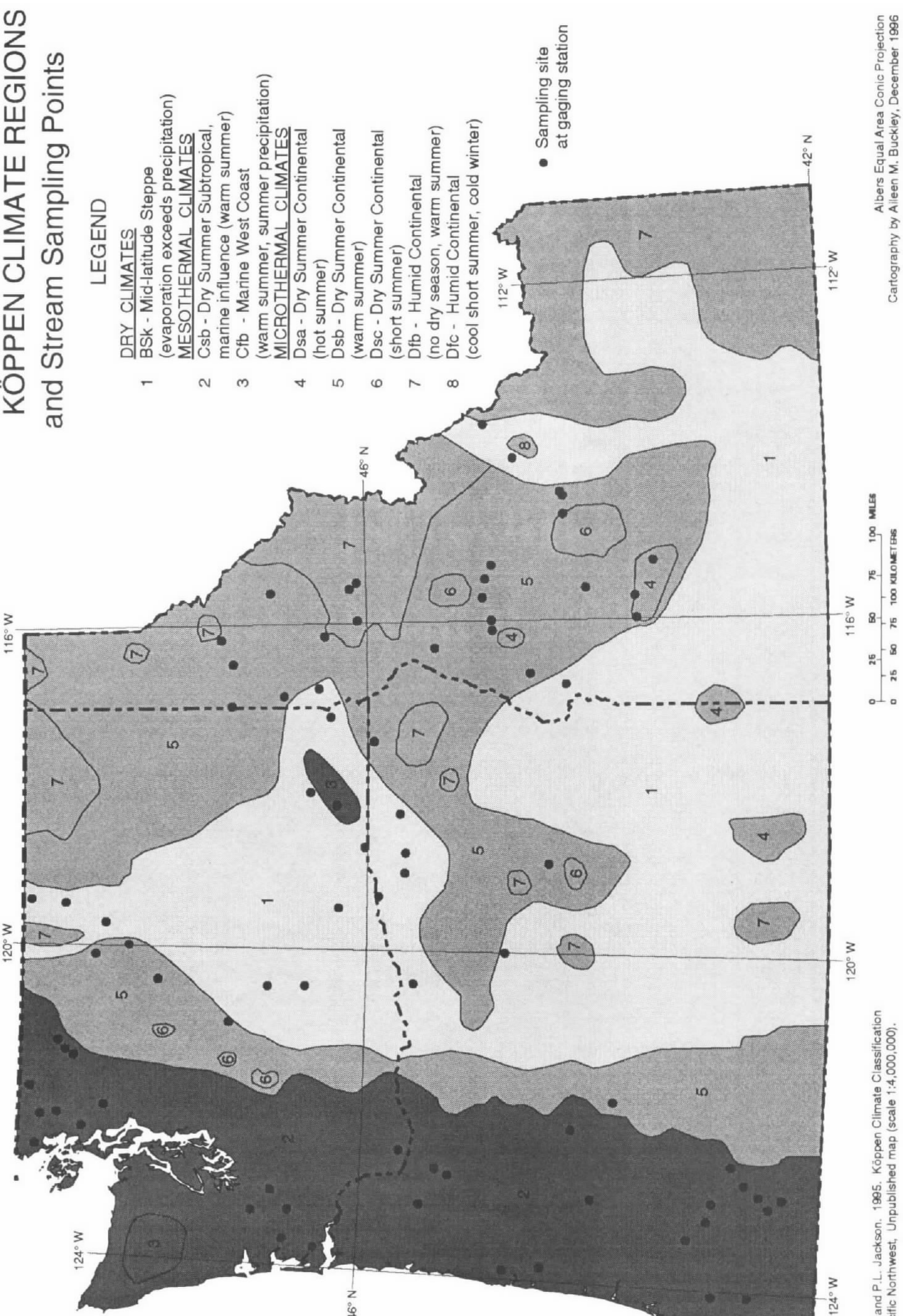

Figure 2. Climate Regions and Stream Sampling Points.

and east, and the Great Basin to the south. This area is composed primarily of horizontal layers of basalt, which have a surface expression of level plateaus or rolling hills. Many of the plateaus have ineffective drainage and are composed of weak rocks (Fenneman, 1946). The Columbia Plateau is distinctive because of the dissected volcanic plateaus, complex mountains, and young incised valleys (Rosenfeld 1985).

North-south trending mountain ranges and a line of great valleys define the Pacific Mountain System. The northern, middle, and southern Cascade Mountains, representing the Cascade-Sierra Mountains, have sharp alpine summits of accordant height and predominant volcanic cones. The Olympic Section is very similar to the Cascades with accordant crests and local alpine peaks. The Oregon Coast Range extends from the Olympic Mountains in Washington south to the Klamath Mountains in southern Oregon. The Klamath Mountains are located west of the Cascades between the Coast Ranges of Oregon and California (Fenneman, 1946). The headwater reaches for many of the streams in this area are in mountainous zones. The streams transition through foothills and alluvial fans and emerge onto alluvial valley floors. The Pacific Mountain System is composed of a diverse array of geologic formations and exhibits striking relative relief.

Homogeneous mountain peak elevations and the lack of distinct directional trends or mountain ranges typify the Rocky Mountain System. The mountainous areas are divided by valleys or canyons. Igneous and metamorphic rocks dominate the headwaters, while lakebed deposits are more typical of the alluvial valleys (Fenneman, 1931). Many of the streams have a relatively high gradient and are confined by steep valley walls.

Ecoregions

Ecoregion Classifications as defined and mapped by Omernik (1987) were used to divide the Pacific Northwest into regional units that include areas of similar geology, topography, climate, vegetation, soils, and major land uses. Four component maps are used to generate the PNW ecoregion map; these include Major Land Uses (Anderson, 1970), Classes of Land-Surface Form (Hammond, 1970), Potential Natural Vegetation (Kuchler, 1970), and soils maps from the Natural Resources Conservation Service and others. Supplementary maps used to verify Omernik's conceptualized regions included Surficial Geology (Hunt, 1979), Physical Divisions (Fenneman, 1946), Land Resource Regions and Major Land Resource Areas of the United States (USDA-SCS, 1981), Climates of the United States (Baldwin, 1973), and the Census of Agriculture (U.S. Bureau of the Census, 1969; 1974; 1978).

The PNW is composed of 16 ecoregions; however, the USGS gaging stations utilized in this study were located in 11 of the ecoregions, organized under three major ecoregion divisions: Pacific Maritime Mountains, Western Cordillera, and the West Interior Basin and Range (Figure 4). The Pacific Maritime Mountains (PMM) support dense forests composed of Redwood, Sitka spruce, cedar, hemlock, Douglas fir, and silver fir. The Western Cordillera (WC) is more arid than most of the Pacific Maritime Mountains and is characterized by Douglas fir forests and cedar-hemlock-Douglas-fir forests. The West Interior Basin and Range (WIBR) is distinctively drier than the other two ecoregions and this is reflected in the vegetation composition of a dominant grassland/shrubland community composed of sagebrush, wheatgrass, rabbit brush, and juniper (Frenkel, 1985).

METHODOLOGY

Data Collection

Each selected gaging station was visited and the following data were collected: bankfull width and depth, channel slope, and bed material size. Bankfull indicators were observed in the field using guidelines set out by Dunne and Leopold (1978). Bankfull indicators include: (1) topographic break from vertical bank to flat floodplain, (2) topographic break from steep slope to gentle slope, (3) change in vegetation from bare to grass, moss to grass, grass to sage, grass to trees, or from no trees to trees, (4) textural change of depositional sediment, (5) elevation below which no fine debris (needles, leaves, cones, seeds) occurs, and (6) textural change of matrix material between cobbles or rocks. Bankfull width was measured at the bankfull elevation and bankfull depth was then determined as an average of the measured depths across the stream channel. Cross-section interval distances varied depending upon overall channel width. Streams up to 40 feet wide were sampled at two-foot intervals, streams 40 to 150 feet wide were sampled at five-foot intervals, and streams greater than 150 feet wide were sampled at ten-foot intervals. Channel slope was substituted for bankfull water-surface slope and was measured in-stream using a transit and stadia rod. Bed material size was measured using the Wolman Pebble Count (Wolman, 1954).

Once the bankfull stage was determined, the stage height was surveyed and the gage height was related to discharge. The annual maximum peak flow

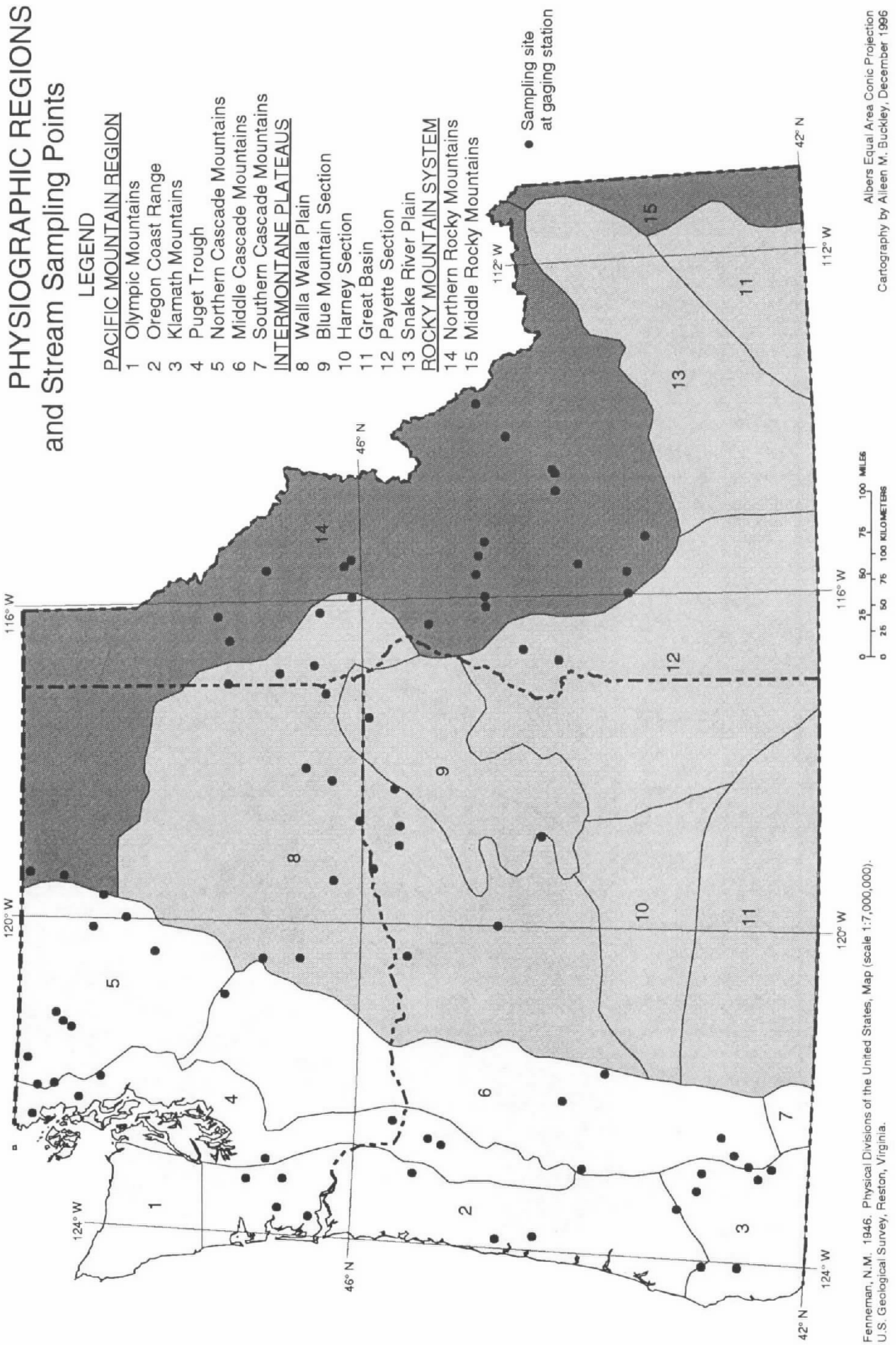

Figure 3. Physiographic Regions and Stream Sampling Points.

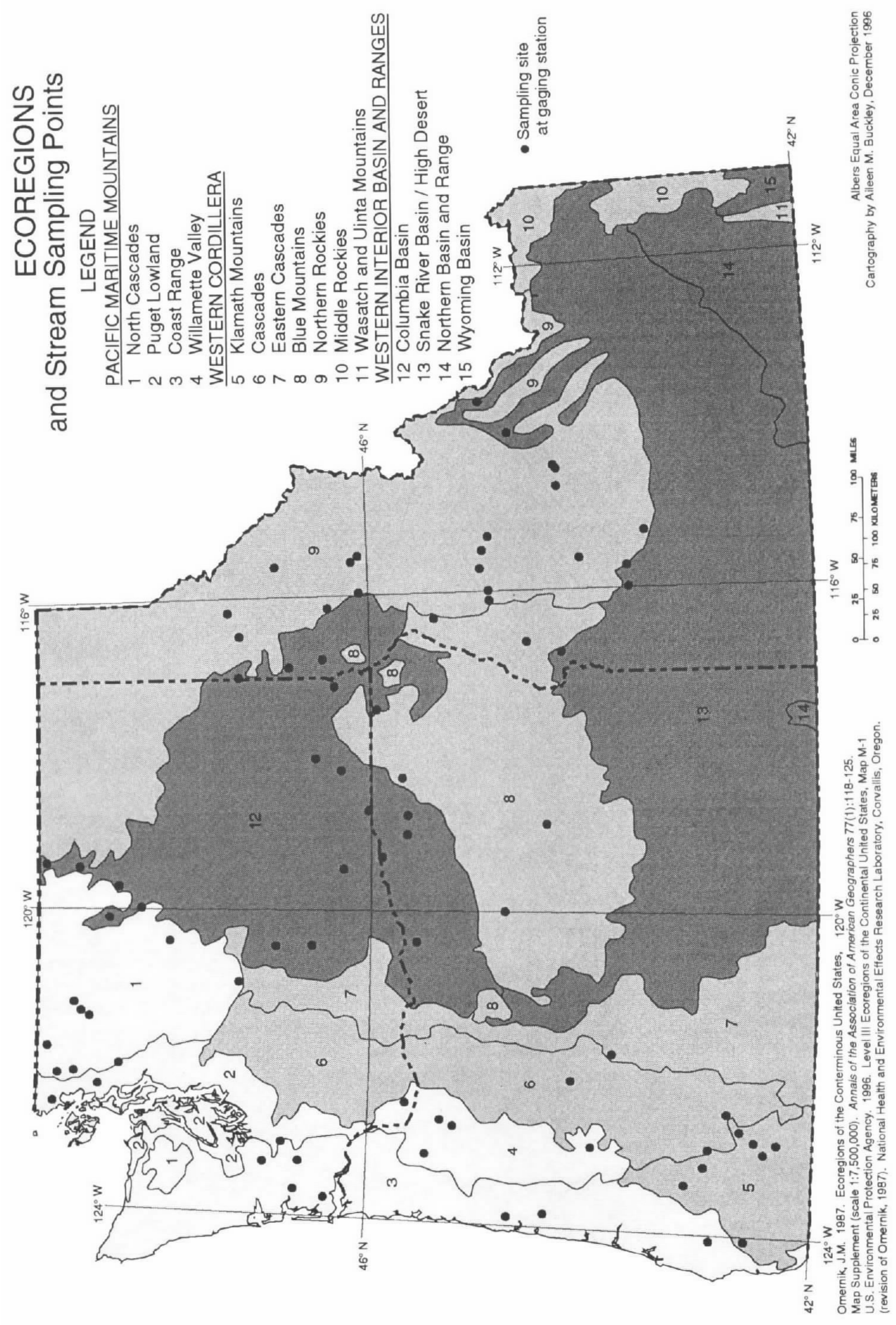

Figure 4. Ecoregions and Stream Sampling Points.

frequency curve was used to determine the recurrence interval.

Data Analyses

Values of T_a were evaluated using an analysis of variance (ANOVA) to determine regional patterns and the associated summary statistics. The data were transformed using a reciprocal transformation to adjust for the non-normal distribution (Ramsey and Schafer, 1993). The T_a values were stratified by climate zone, physiographic province, and ecoregion. The regionalization factors were based on: (1) climatic patterns which affect stream discharge and vegetation; (2) physiography which influences the characteristics of the bedload, channel banks, and channel bed; and (3) ecoregions which combine vegetation and physiography, thereby regionalizing many of the factors that are thought to control the shape of the stream channel. These groups were analyzed using an ANOVA to determine differences between group means and the Kruskal-Wallis non-parametric test to verify that the ANOVA results were not highly influenced by outlying observations.

The data were initially analyzed as one large sample to develop very general hydraulic geometry relationships for the entire PNW region using simple regression techniques (ANOVA). After the initial analysis and determination that ecoregion is the most statistically significant spatial relationship, the data were stratified into ecoregions and regression equations were generated for three Level III Ecoregions.

Eight regression equations were developed for all of the streams sampled in the Pacific Northwest study area as a group and the same variables were used to generate eight regression equations for each of the three major ecoregions. The dependent variables include bankfull width, depth, area and discharge, while the independent variables include drainage area and bankfull discharge. Utilizing the two equations that relate width to discharge and depth to discharge, a third equation representing the relationship between velocity and discharge was derived based on the equation Q = AV (where Q = discharge, A = area, and V = velocity).

Combining the following equations (Dunne and Leopold, 1978):

$$w = aQ^b \qquad d = cQ^f \qquad v = k\,Q^m$$

where w = width, d = depth, v = velocity, Q = discharge, and a, b, c, f, k, and m are constants. It follows that:

$$wdv = (aQ^b)\,(cQ^f)\,(kQ^m)$$

$$Q = (ack)Q^{(b+f+m)}$$

therefore:

$$ack = 1, \text{ and}$$

$$b + f + m = 1.$$

The a, b, c, and f variables were derived using field data, while the k and m variables were calculated.

The data were transformed with a natural logarithm to adjust for nonconstant variability in the data set and also to adjust for skew. When logarithmic data is back-transformed to its original scale, the data represents median values rather than mean values. Since all of the data in this study were transformed, all values generated using the regression equations represent median values.

RESEARCH RESULTS

The T_a data were stratified by broad climatic zones. The three groups were compared and there is conclusive evidence to support a difference in mean values of Ta (p-value = 0.01) (Table 2). By reviewing the statistical similarities of each group, Köppen climates B and D appear to have close mean values while C climates are substantially different. Therefore, based on a statistical comparison of means, the B and D zones were incorporated as a single region (BD). A further rationale for combining the climate zones was based on the origin of the streams in these areas; the streams running through B climate zones originate in highlands classified as D climates and reflect the hydrology of these more humid, highland areas. The BD and C climate zones, when compared to one another, illustrate significant statistical differences. Ultimately, two broad climate regions emerge as hydrologically important for the Pacific Northwest, one represented by the Csb and Cfb climates and the other represented by the combination of BSk, Dsa, Dsb, and Dsc climates, more simply stated as an east/west divide at the crest of the Cascade Range.

The stream data were then stratified by three broad physiographic regions: the Rocky Mountain System, the Intermontane Plateaus, and the Pacific Mountain System. Statistical evidence indicates that these three groups share the same average T_a indicating that regionalization by physiographic province is not meaningful in this context (p-value = 0.22).

TABLE 2. Bankfull Discharge Summary Statistics.

Group	Subgroup	Sample Size	Reciprocal Average	Kruskal-Wallis Average Rank
Climate	BD	44	.7173	44.41
	C	31	.8354	28.90
	p-value		0.0140	0.0024
Physiography	RMS	21	.7189	45.93
	IP	18	.7672	39.94
	PMS	36	.8141	32.40
	p-value		0.2167	0.0702
Ecoregion	PMM	17	.9318	16.44
	WC	37	.7126	46.38
	WIBR	21	.7624	4.69
	p-value		0.0005	0.00001

There is conclusive evidence that the Pacific Maritime Mountains, Western Cordillera, and West Interior Basin and Range Ecoregion Divisions do not share the same average T_a (p-value = 0.0005). The Western Cordillera and the West Interior Basin and Ranges have very similar values; but this may be a result of the hydrologic linkages between the contributing Western Cordillera watersheds and the receiving Western Interior Basin and Range streams as mentioned above.

The 76 stream sites in the study area have T_a values which range from a low of a 1.0-year flow event to a high of a 3.1-year flow event. The mean value for bankfull recurrence in the PNW is 1.4 years. The data are negatively skewed with a mode value of 1.0 (Table 3). A reciprocal transformation was used to correct for the non-normal distribution of these data.

TABLE 3. Bankfull Discharge Recurrence Intervals for Major Ecoregion Divisions.

T_a	All PNW Streams	Pacific Maritime Mountains	Western Cordillera	Western Interior Basin and Range
Average	1.4	1.2	1.5	1.4
Median	1.2	1.0	1.4	1.3
Mode	1.0	1.0	1.2	1.1
Standard Deviation	0.5	0.5	0.5	0.5

Based on the significance of the relationship between ecoregion divisions and T_a, hydraulic geometry regression equations were developed for the three ecoregions represented in the PNW. The regional relationships were derived from field data except for the equation incorporating velocity, which was derived mathematically. The equations derived from field data have an associated R-squared value, which indicates how well the derived equation fits the data (Table 4).

The R-squared values for the equations relating bankfull width to bankfull discharge are very similar between all three major ecoregions and the entire Pacific Northwest (0.76, 0.87, 0.84). Two of the three ecoregions have slightly higher R-squared values than the Pacific Northwest (WIBR and WC). There is more variability among the R-squared values for the bankfull depth versus bankfull discharge equations from Table 4 (0.59, 0.83, 0.54).

The PMM ecoregion rated the poorest among the three ecoregions based on the fit of the regression models to the data. The regression equations representing all of the PNW are almost as strong as the regression equations developed specifically for the PMM ecoregion, which indicates significant variability in the data for the PMM.

The WIBR regression equations overall have very high R-squared values. This indicates lower variability in the data resulting in a tighter fitting model. This could be the result of the WIBR ecoregion, which has relatively uniform hydrologic conditions (snow dominated) as compared to the PMM ecoregion, which has extensive hydrologic variability (rain, rain-on-snow, and snow dominated).

The WC ecoregion has two very strong regression equations, bankfull width and bankfull depth versus bankfull discharge. The regression equations relating stream data to drainage area are not as strong. This indicates high variability in physical attributes of the watershed, such as slopes or snow pack, but also indicates that the channel morphology is strongly controlled by bankfull discharge events.

TABLE 4. Regional Hydraulic Geometry Regression Equations for PNW Streams.

Regression Equation	R-Squared (percent)
Pacific Northwest Streams – N = 76	
$A = 0.548Q^{0.864}$	81.0
$A = 10.89DA^{0.643}$	49.3
$Q = 50.93DA^{0.67}$	44.3
$w = 2.34Q^{0.49}$	81.0
$w = 11.80DA^{0.38}$	48.9
$d = 0.22Q^{0.38}$	75.9
$d = 1.13DA^{0.24}$	29.0
$v = 1.95Q^{0.13}$	
Pacific Maritime Mountain Streams – N = 22	
$A = 0.454Q^{0.913}$	81.0
$A = 14.26DA^{0.739}$	64.0
$Q = 91.05DA^{0.67}$	45.7
$w = 2.37Q^{0.50}$	76.0
$w = 12.39DA^{0.43}$	58.7
$d = 0.15Q^{0.45}$	61.9
$d = 0.66DA^{0.39}$	48.7
$v = 2.81Q^{0.05}$	
West Interior Basin and Range Streams – N = 22	
$A = 0.502Q^{0.86}$	71.0
$A = 1.904DA^{0.784}$	78.5
$Q = 13.05DA^{0.77}$	79.4
$w = 0.96Q^{0.60}$	86.8
$w = 3.27DA^{0.51}$	82.9
$d = 0.36Q^{0.31}$	72.0
$d = 0.79DA^{0.24}$	58.4
$v = 2.89Q^{0.09}$	
Western Cordillera Streams – N = 32	
$A = 0.817Q^{0.806}$	88.0
$A = 2.94DA^{0.857}$	77.0
$Q = 17.28DA^{0.86}$	51.3
$w = 3.50Q^{0.44}$	84.4
$w = 9.40DA^{0.42}$	53.6
$d = 0.20Q^{0.39}$	87.4
$d = 0.61DA^{0.33}$	44.2
$v = 1.43Q^{0.17}$	

Nomenclature:
- Q = bankfull discharge (cfs).
- DA = drainage area (mi^2).
- A = bankfull cross-sectional area (ft^2).
- w = bankfull width (ft).
- d = bankfull mean depth (ft).
- v = bankfull mean velocity (fps).

In all four groups, the equations with discharge (Q) as the independent variable have higher R-squared values than the equations with drainage area (A) as the independent variable. This indicates the strong relationship between bankfull discharge and channel geometry compared to the weaker relationship between drainage area and channel geometry, and drainage area and bankfull discharge.

CONCLUSIONS

Average T_a for the entire PNW study area is 1.4 years. This is lower than the model 1.5-year average discussed by other authors (Dury *et al.*, 1963; Leopold *et al.*, 1964; Hickin, 1968; Dunne and Leopold, 1978; Leopold, 1994) but is certainly within the general range of one to two years and strongly supports the assumption that the 1.5-year flow event approximates bankfull discharge. The range of recurrence intervals in this study (1.0 to 3.1 years) does not correspond to the findings of Williams (1978) (one to 32 years). This research shows that by using a regionalization scheme, T_a can be further refined for specific areas within the Pacific Northwest, thus providing added information for habitat classifications, erosion estimates, and restoration project evaluations. A 1.5 year T_a should be applied to streams in Idaho, eastern Washington, and eastern Oregon, while a 1.2 year recurrence interval should be applied to streams in the more humid areas of western Oregon and western Washington.

Of the three regionalization schemes tested, the Ecoregion Level III Classification incorporates the most statistically significant spatial factors related to T_a (two-sided p-value = 0.0005). However, climate regionalization is also significantly related to T_a (two-sided p-value = 0.0140).

The Köppen climate classifications represent the annual and seasonal temperature and precipitation regimes to which regional terrestrial biomes respond. These regional vegetation associations also form a major component of Level III Ecoregions. Present day climate, and climatically adapted vegetation associations appear to be the underlying factor influencing T_a. In the more humid areas of western Washington and Oregon, bankfull discharge is achieved more frequently and for longer periods. In the more arid areas of eastern Washington and Oregon and all of Idaho, bankfull events are less frequent, and can range from short rainfall induced events to longer snow-melt induced events. Interception of rainfall by vegetation, time of concentration, and vegetative stability in streambanks all influence the size and shape of the bankfull channel. It is reasonable to infer that a dense, well-vegetated watershed and riparian zone attenuate streamflow to the extent that a smaller channel cross-section can be maintained. This would indicate that we can predict, on a relative scale, the average T_a of streams based on vegetative and climatic similarities.

The regionalization scheme is scale dependent. While climate is shown as a major contributing factor at the PNW regional scale, other factors may control the variability of T_a within a single, broad regional climatic zone. While Ecoregion Classifications correlate well with stream response characteristics, it is not clear which of the many factors within the Ecoregion concept directly influence T_a. It is clear, however, that at the PNW regional scale, climate is a significant factor, while physiography is not.

Further analyses of T_a will provide additional data to refine the relationship between physical environmental factors, here represented by ecoregion, climate, and physiography, and T_a. A similar methodology could be employed in any part of the United States to derive appropriate values of T_a for those regions. When using approximations or averages of physical characteristics, geographically delineating the limits of these averages is critically important to reduce misapplication of the tool. With the diversity of climatic regions, geomorphic provinces, and vegetative zones in the United States, a generalized bankfull recurrence interval (such as 1.5 years) has only limited application. By refining values of T_a to geographic regions, we can better understand and quantify the diversity of stream systems.

By developing three regional relationships and five hydraulic geometry relationships for each of the three ecoregions representing the PNW, it is possible to evaluate some of the controlling factors of channel hydraulics at the PNW regional level. When working in the WIBR ecoregion, using any of the eight regression equations may be appropriate. However, when working in the WC ecoregion, it would be more valuable to rely on the regression equations that contain bankfull discharge as the independent variable because the R-squared value is considerably higher than in the other regression equations; however, this will be difficult for ungaged streams. Manning's, or other flow continuity equations, can be used to estimate a discharge for the bankfull channel cross-section identified in the field. These discharge estimates could then be compared to regional equations to determine if the bankfull discharge is within the appropriate range for recurrence intervals for that region.

The PMM ecoregion regression equations are overall only a slight improvement over the PNW regression equations. When more data become available in the PMM ecoregion, it may be possible to further stratify the data and develop regression equations for smaller regions within the PMM. This may eliminate some of the large-scale physical variability, such as hydrologic regime (rain-dominated versus snow-dominated systems), of the PMM ecoregion and result in stronger regression equations.

Regional regression equations are a valuable tool for individuals working on gaged and ungaged streams alike. The more refined the regression equations are for respective regions, the more accurate the estimates of hydraulic geometry parameters will become. For this study we developed a set of relationships that can be used specifically on PNW streams, a process that needs to occur in other regions as well. With these expanded data, we will be able to accurately and objectively compare the hydraulic geometry of streams throughout the United States and eventually throughout the world.

ACKNOWLEDGEMENTS

This paper was substantially improved by the comments of Dave Rosgen, Frank Reckendorf, Lyle Steffen, and three anonymous reviewers. The Natural Resources Conservation Service funded this study.

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